

# Report on the Stanford/Ames Direct-Link Space Suit Prehensor

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## Abstract

Researchers at the Center for Design Research at Stanford University, in collaboration with NASA Ames at Moffet Field, California, are developing hand-powered mechanical prehensors to replace gloves for EVA spacesuits. This paper covers the design and functional properties of the first version "Direct Link Prehensor" (DLP). It has a total of six degrees-of-freedom and is the most elaborate of three prehensors being developed for the project. The DLP has a robust design and utilizes only linkages and revolute joints for the drive system. With its anthropomorphic configuration of two fingers and a thumb it is easy to control and is capable of all of the basic prehension patterns such as cylindrical or lateral pinch grasps. Kinematic analysis reveals that, assuming point contacts, a grasped object can be manipulated with three degrees-of-freedom---yet in practice more degrees-of-freedom are possible.

## 1.0 Introduction

One of the greatest difficulties astronauts encounter during EVA is simply the use of their hands, resulting primarily from the high stiffness of the gloves due to the suit's pressurization. Although space suit glove technology has improved markedly in the past several years, the higher suit pressures expected for future EVA's will significantly offset these improvements. This and other considerations provide the motivation for the development of hand-powered space suit prehensors (see the reference article [3] for more general background on the prehensor project).

The primary goal for the design of the DLP was to incorporate as many degrees-of-freedom as possible while maintaining ruggedness and reliability. An anthropomorphic configuration was selected partly because of its proven effectiveness and partly because of the difficulty humans have with simultaneously controlling more than two or three degrees-of-freedom unless the corresponding motions are "natural".

The motion of the operator's hand is conveyed to the mechanical fingers by a system comprised purely of linkages connected by revolute joints. The minimization of moving parts, along with the absence of cables or gears, results in the DLP possessing smooth, accurate, and sensitive finger control with good force/position reflection.

## 2.0 Finger Geometry and Control

Figure 1 shows two photos of the DLP (version I) and indicates the basic components of the device, namely, the mechanical fingers, the "shroud ears", and the control mechanisms. Note that the entire shroud has not been completed yet. It shall be molded of fiberglass around the shroud ears and provide a pressurized environment around the astronaut's hand. The whole assembly will then be attached to the space suit in the same manner as a glove. The first version DLP shown in the photographs can fit approximately 95% of the U.S. male population and withstand large grip forces (roughly 150 pounds). Note that most of the DLP is fabricated from aluminum.

The motion of each mechanical finger/thumb of the DLP is restricted to a corresponding plane, as best observed in Figure 2, and the planes of motion are all perpendicular to a common plane called the "palm plane" (this phrase is used in the following only to connote orientation, i.e., the

position of the palm plane is not important). The angle between the planes of motion of the mechanical "index" and "ring" fingers is fifteen degrees. In the following, it is convenient to define the "average finger plane of motion" (AFPM) as that plane which is also perpendicular to the palm plane and which bisects the angle between the index and ring mechanical finger planes of motion. The angle between the plane of motion of the mechanical "thumb" and the AFPM is fifty-five degrees. The index and ring fingers are separately oriented such that their tips almost touch when the fingers are substantially curled, hence providing tip prehension for small objects.

Figure 3 shows plan and side views of the index and ring finger control assemblies, without the shroud ears. The index and ring fingers are identical in construction and each have three links, referred to as the proximal, medial, and distal links, and three corresponding revolute joints. Each finger, however, has only two degrees-of-freedom since the motions of the medial and distal links are coupled by a coupler linkage. This coupling results in a curling motion of the fingers similar to that exhibited by human hands, and is particularly useful for "power grasps" such as cylindrical or spherical grasps (see Sec. 4.0). Note that a "palm" is attached to the shroud ears (see Figure 1a) to assist in these types of grasps.

The motion of the operator's hand is transmitted through a system of control linkages (see Figure 3). These linkages, along with the pushrods, form a set of (approximate) parallelograms which keep the mechanical fingers in the same orientation as the control linkages. In order to provide controls which operate most comfortably, the joints of the control linkages should pass through the corresponding joints of the hand. However, the planes of motion for the control linkages for the (mechanical) index and ring fingers are parallel--which is not the case for a human hand since the proximal (or metacarpophalangeal) joints for the latter form an arch. This fact is manifested as a slight discomfort when the hand of the operator is closed (in a fist). The DLP could be constructed such that the said planes correspond more closely to a human hand, but the shroud was found by the author to be impractically large due to the resulting mechanism.

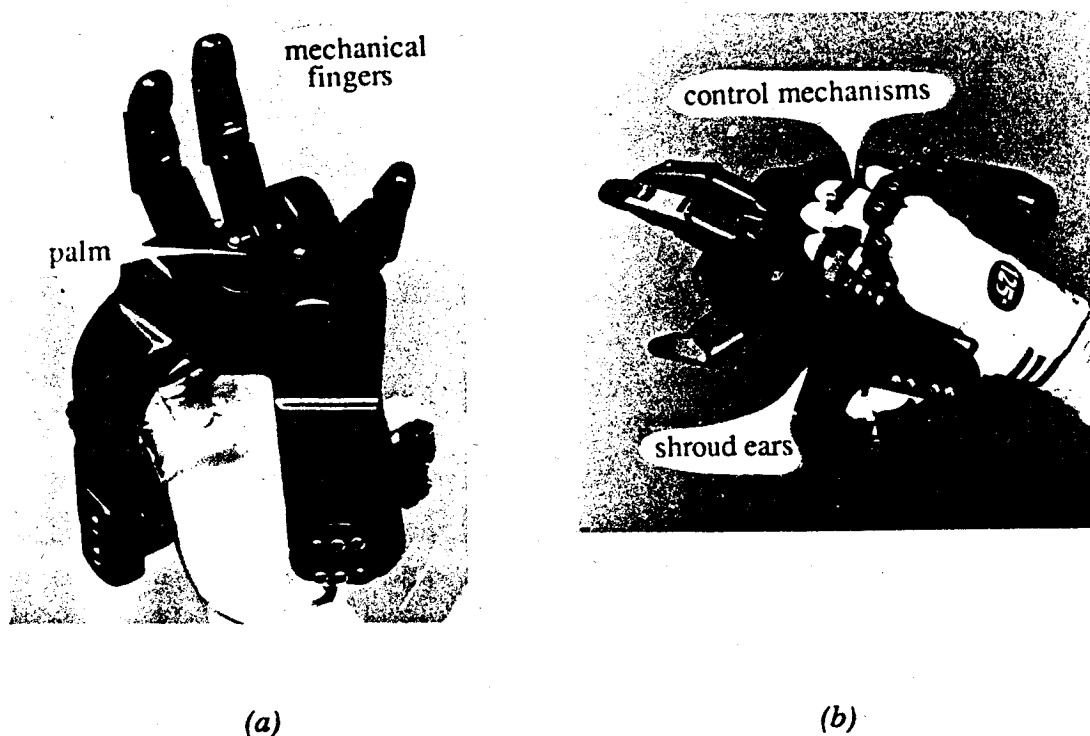


Figure 1 Photos of the first version DLP

Motion is imparted to the control linkages through the medial and distal links (or second and third phalanges) of the operator's hand, and each phalange tailor-fitted to a ring attached to a corresponding control linkage. For the thumb, both the proximal and distal links (or first and third phalanges) have ring attachments to the control linkages.

Control of the DLP is natural since the configuration of the mechanical fingers parallels that of the operator's hand; in a sense, the mechanical fingers appear as a "projection" of the human fingers which control them. The thumb and index fingers of the operator control the similarly juxtaposed mechanical thumb and index finger; the mechanical ring finger is controlled by moving the operator's middle, ring, and little fingers in unison. The only possible alternative for control allocation would be to let the operator's little finger alone control the mechanical ring finger since it is virtually impossible for one to move his or her index and middle fingers (in unison) independently of the ring and little fingers (in unison).

As with the mechanical fingers, the motions of the medial and distal control linkages are coupled by a coupler linkage (see Figure 3). Although the distal control linkages are not absolutely necessary to control the motion of the mechanical fingers, they are included to facilitate the fine control needed for manipulation of objects. In order to minimize the weight (and inertia) of the controls, the distal control linkages have low mass and strength properties. However, when the operator imparts a grip force on the distal linkages over a prescribed amount, damage is avoided by mechanical override mechanisms which allow the distal linkages to rotate beyond the positions determined by the coupler linkage.

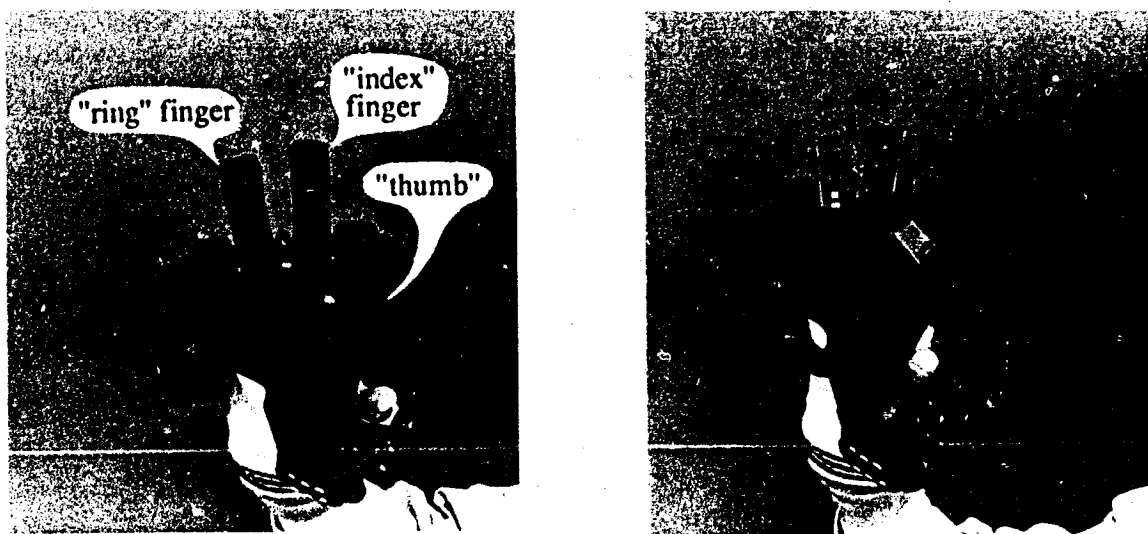
The ratio of motion of the control linkages to the mechanical fingers is approximately 1.00 to 1.07. This essentially allows the mechanical fingers to reach useful positions which would otherwise result in collisions between parts of the control linkages.

The first version DLP incorporates ball bearings for the control linkages and bushings for the remaining joints. With this arrangement, most of the friction in the drive system arises from the teflon rotary seals located around the concentric shafts (two shafts for each finger/thumb), the axes of which pass through the corresponding proximal joints of the mechanical fingers/thumb. These seals allow transmission of finger motion via rotary motion across the pressure differential of the shroud wall.

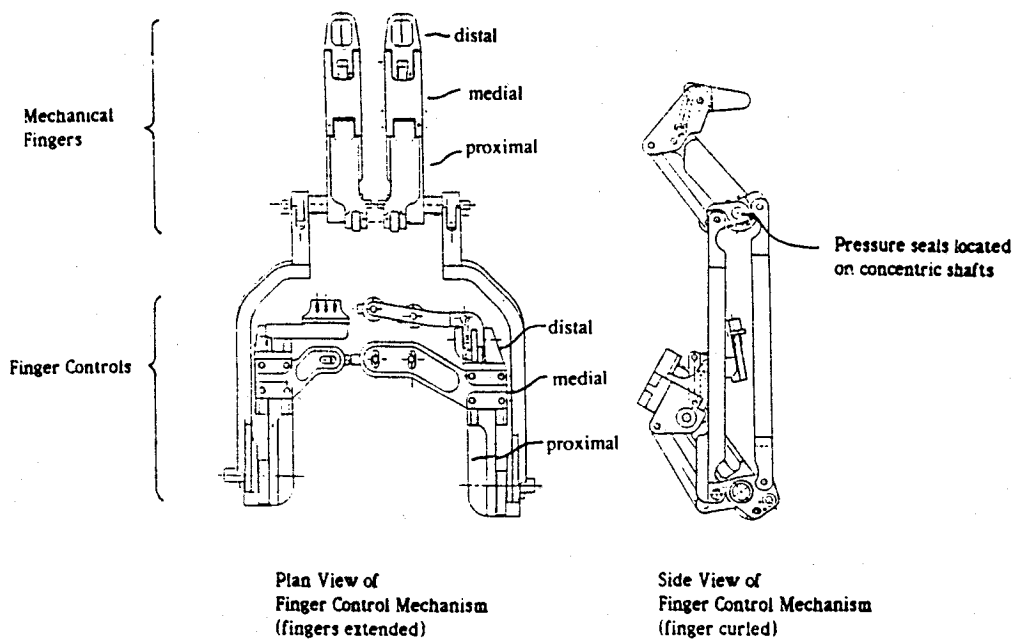
### 3.0 Other Geometric Characteristics

An important factor affecting prehensor (and glove) performance is the location of the "neutral position" of the suit's flexible wrist joint compared with that for the operator's hand. The neutral position of the operator's wrist corresponds to the long axis of his forearm when the latter, along with the palm of the hand, is laid flat on a supporting surface. From this position the wrist can be flexed and extended approximately equal angles. Ideally, this position also corresponds to the neutral position of the wrist joint for the suit, a circumstance determined by the prehensor (or glove) design. As shown in Figure 4, for the first version DLP the operator's hand is extended approximately twenty degrees beyond its neutral position for the corresponding neutral position of the wrist assembly, which unfortunately results in twenty degrees less extension capability than the ideal case (note that  $z_w$  is the neutral axis for the wrist joint, and  $z_{oh}$  is the neutral axis for the operator's wrist). This disadvantage stems from the presence of the thumb control mechanism---a problem which shall be addressed for future designs to a degree proportional to how badly the overall performance of the DLP is affected. Note that the diminishment of wrist mobility is not a problem for gloves.

Another factor affecting prehensor performance is the geometrical relation between the mechanical finger ensemble and the operator's hand. Denoting a reference frame fixed with respect to the mechanical finger ensemble as MH (for "mechanical hand"), and denoting a similar frame fixed with respect to the hand as OH, then for a hypothetical prehensor design six parameters are needed to specify the position and orientation of OH with respect to MH. How these parameters affect overall EVA performance depends partly on ergonomic considerations, such as having the task space comfortably located in front of the operator's face, and partly on manipulation issues,



*Figure 2 Planes of motion for the mechanical fingers*



*Figure 3 Plan and side views of the index and ring finger control assemblies (shroud omitted)*

such as the ability of the operator to map the mechanical finger motions/forces to his own motions/forces. The configuration for the DLP, described in the next paragraph, resulted to a large extent from the desire to implement the uncomplicated linkage system.

Figure 4 shows the relationships between the MH and OH cartesian frames for the first version DLP when the wrist joint is at its neutral position, where the x-axes of both frames are perpendicular to the page. The orientations of OH and MH are identical and the xz-plane of each corresponds to the plane of the fingers when they are fully extended. Each respective x-axes lies along a line (approximately) connecting the corresponding first (or metacarpophalangeal) joints. Note that  $p$  is the position vector of the origin of MH with respect to OH---it lies in the yz-planes of MH and OH and is 6.25 inches long.

#### 4.0 Prehension Patterns

In spite of the limitation of planar motion of the mechanical fingers, the DLP is capable of all the basic prehension patterns and, when in the hands of a moderately experienced operator, can manipulate objects with a surprising degree of dexterity. Figure 5 shows three forms of tip prehension which are commonly used for manipulative tasks. Figure 6 shows (a) cylindrical, (b) spherical, and (c) lateral pinch grasps. The former is especially important for astronaut mobility because of the use of hand rails for EVA locomotion. Figure 7a shows a useful grasp for turning a screw driver (by rotating the forearm), and Figure 7b shows how a powered rotary tool can be operated.

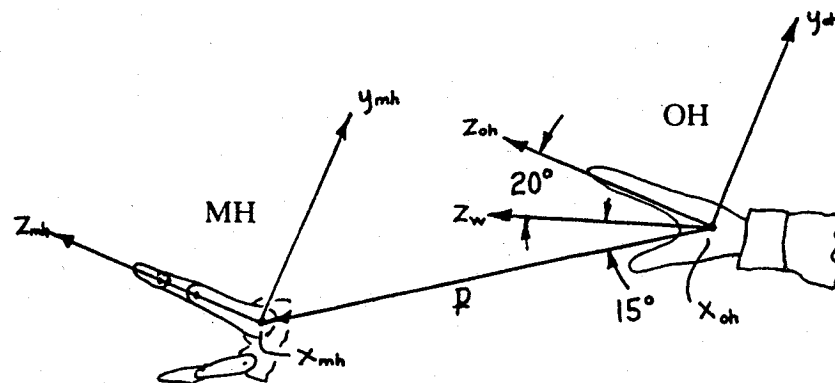


Figure 4 The neutral axes and the relationship between MH and OH

#### 5.0 Manipulative Capability

Tip prehension is the most common pattern used for manipulation, and for the DLP this may be with either two or three finger tips. For the latter case, assuming point contacts between the finger tips and the object, kinematic considerations reveal that the object can be manipulated with three degrees-of-freedom with respect to the hand. However, since sliding can occur at some contacts without seriously disrupting the stability of the grasp, manipulations which do not quite conform to the above ideal case are possible. Considering the idealized case presently, the velocity of a contact point on the object can be written as

$$v_i = v_0 + \omega_0 \times r_i, \quad \text{for } i=1,2,3 \quad (1)$$

where  $v_i$  is the velocity vector of the  $i$ th contact,  $v_0$  and  $\omega_0$  are the velocity vector and angular



(a)



(b)



(c)

*Figure 5 Three forms of tip prehension*



(a)

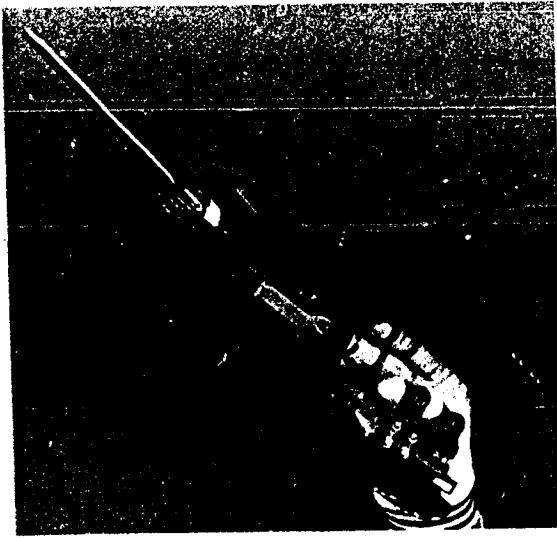


(b)

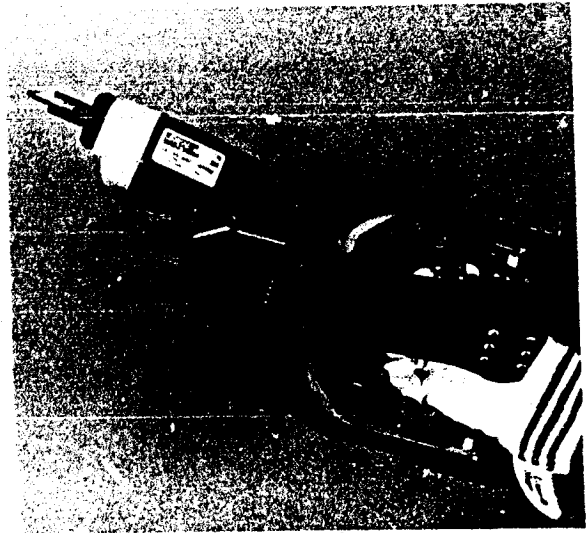


(c)

*Figure 6 Cylindrical, spherical, and lateral pinch grasps*



(a)



(b)

Figure 7 Two other useful grasps for the DLP

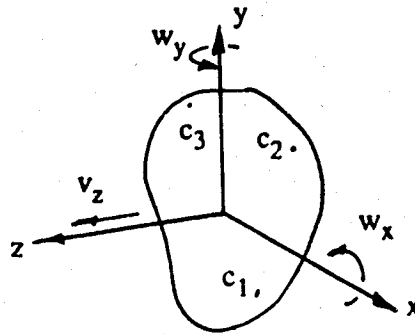
velocity vector, respectively, of the object with respect to the hand, and  $r_i$  is the position of the  $i$ th contact in the object reference frame. Each contact must move in a corresponding (mechanical finger motion) plane, and, defining these planes by their normal unit vectors  $P_i$ ,  $i=1,2,3$ , this requirement can be written as

$$P_i \cdot v_i = 0, \quad \text{for } i=1,2,3. \quad (2)$$

Combining eqs. (1) and (2) and expressing the result in matrix form gives:

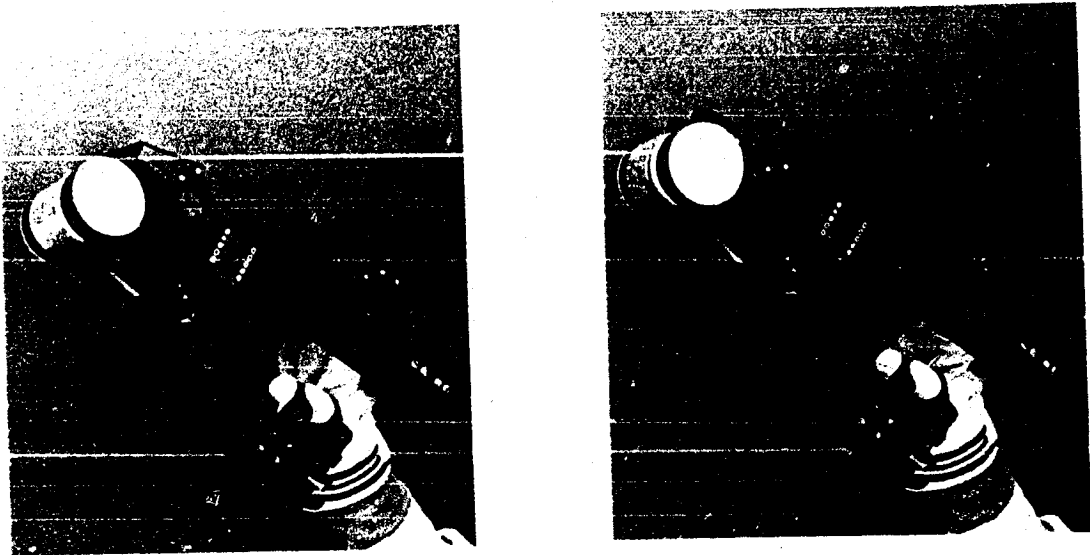
$$\begin{pmatrix} (-r_{z,1}P_{y,1} + r_{y,1}P_{z,1}) & (r_{z,1}P_{x,1} - r_{x,1}P_{z,1}) & (-r_{y,1}P_{x,1} + r_{x,1}P_{y,1}) & P_{x,1} & P_{y,1} & P_{z,1} \\ (-r_{z,2}P_{y,2} + r_{y,2}P_{z,2}) & (r_{z,2}P_{x,2} - r_{x,2}P_{z,2}) & (-r_{y,2}P_{x,2} + r_{x,2}P_{y,2}) & P_{x,2} & P_{y,2} & P_{z,2} \\ (-r_{z,3}P_{y,3} + r_{y,3}P_{z,3}) & (r_{z,3}P_{x,3} - r_{x,3}P_{z,3}) & (-r_{y,3}P_{x,3} + r_{x,3}P_{y,3}) & P_{x,3} & P_{y,3} & P_{z,3} \end{pmatrix} \begin{pmatrix} w_0 \\ v_0 \end{pmatrix} = 0 \quad (3)$$

where  $P_{x,i}$ ,  $P_{y,i}$ , and  $P_{z,i}$  are the components of  $P_i$ , and  $r_{x,i}$ ,  $r_{y,i}$ , and  $r_{z,i}$  are the components of  $r_i$  (for  $i=1,2,3$ ). The homogeneous solutions to eq. 3 represent the possible motions of the object with respect to the hand. For the DLP the matrix in eq. (3) has a rank of three and hence there are  $(6-3=3)$  three homogeneous solutions. Figure 8 shows an object grasped at three points ( $c_1$ ,  $c_2$ , and  $c_3$ ) on the  $xy$ -plane of the object frame, and this plane is defined to be parallel to the palm plane. The columns of the matrix corresponding to  $w_x$ ,  $w_y$ , and  $v_z$  (the  $x$  and  $y$ -components of



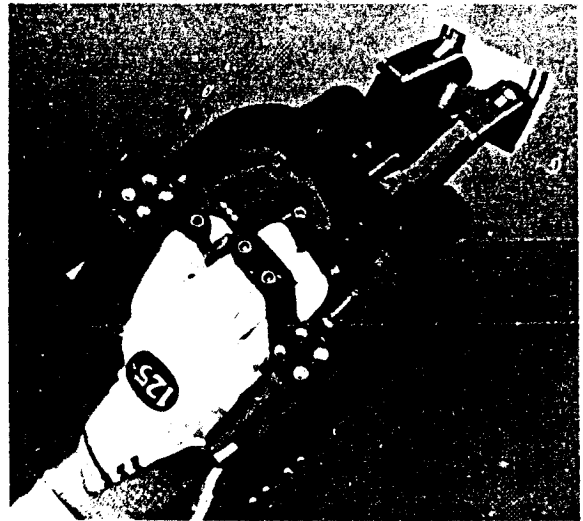
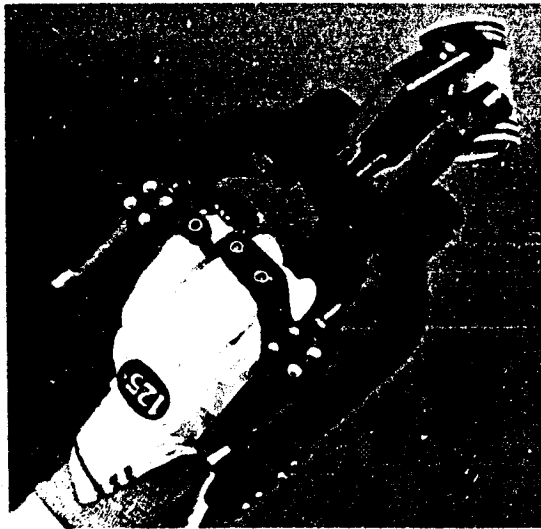
*Figure 8 Manipulative components for the DLP grasping an object with all contacts on a plane parallel to the palm plane*

$\underline{w}_0$  and the z-component of  $\underline{v}_0$ , respectively) for this case are all completely filled with zeroes, indicating that the object can be manipulated with arbitrary magnitudes of  $w_x$ ,  $w_y$ , and  $v_z$  (these components are indicated on Figure 8). Note that this is only the case when all contacts are in a plane parallel to the palm plane. For either rotation components ( $w_x$  or  $w_y$ ), this occurs at the onset of the motion since either rotation moves the contacts out of the (palm) plane---whereupon slightly different homogeneous solutions apply. Figure 9 shows a sequence of photos indicating the motion components  $w_x$  and  $v_z$  (unfortunately, the author does not presently have photos which show these motions uncoupled) and Figure 10 indicates the rotation component  $w_y$  for a cylindrical object grasped by the DLP.



*Figure 9 A sequence indicating the  $w_x$  and  $v_z$  motion components*





*Figure 10 A sequence indicating the  $w_y$  motion component*



*Figure 11 A sequence indicating a motion not conforming to the idealized three point contact case*

In practice manipulations can be performed with the DLP that do not comply with the idealized case just described. For example, almost pure rotation about the y-axis ( $w_y$ ) can be imparted to the object even when the contacts are not contained in x-y plane since this motion entails only a small amount of sliding at the contacts (note that Figure 10 indicates a rather larger angular displacement). Another example is revealed in Figure 11, which shows a sequence indicating a motion which contains primarily a rotation component about the z-axis and a translation component in the x-y plane (this also involves a small amount of sliding motion).

## 6.0 Conclusion

One factor affecting the acceptability of the DLP which has not been discussed much is how comfortable it is to wear and operate. Presently the controls have rings which are custom fitted around the operator's fingers. It may be desirable to make these rings adjustable in diameter and to make them semi-rigid structures. The location of the joint axes of the control mechanisms, as well as the location of the rings themselves also play an important role in the overall comfort of the DLP. An effort is currently underway to provide for more adjustment capability so that one DLP could fit a wide range of hand sizes without any significant re-assembly.

A drawback to the DLP is its somewhat large shroud size (recall, however, that the model shown in the photos is for a large hand size and the author has rather small hands). The main contributor to this condition is the requirement for the shroud to encompass the operator's hand for its full range of motion---another is the space needed for the control mechanisms. The former could be made less of a factor by reducing the ratio of motion of the operator hand to the mechanical hand (and perhaps compensating for the lack of force capability by some sort of power assist). The effect of the latter contributor---particularly on the width of the shroud---might be minimized by alternate mechanisms which hopefully place the control joint axes near those of the operator's hand, although the author has not yet conceived of any practical embodiments.

Another area for improvement of the DLP is in its manipulative capability, although the concomitant increase in mechanism complexity may impede this effort for awhile. Assuming ideal three point contact (with no sliding), at least nine independently controlled joints would be needed to impart arbitrary motions to the object---a configuration which is used for the Stanford/JPL Hand [1]. The likely locations for the additional degrees-of-freedom for the DLP would be to add lateral motion capability to each mechanical finger and the thumb. The thumb seems to be the best candidate initially (for a lateral motion capability) since it could, besides improving dexterity, more significantly enhance the number of prehension patterns. Note that the angle of the thumb plane with respect to the finger planes of motion for the DLP was based partly on a study done by Lozach [2], who found that an angle of forty five degrees seemed to be optimum for many tasks.

Preliminary results with the DLP have shown that the device may indeed be useful for EVA's. Further evaluation will commence after completion of the shroud. The DLP will then be connected to the NASA/Ames AX-5 Hard Suit for testing in the Ames neutral buoyancy tank.

## 7.0 Acknowledgements

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## 8.0 References

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